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REVIEW ARTICLE

Critical Review of Uroflowmetry Methods

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Abstract

Greater than 60% of men (age 40+) are affected by lower urinary tract symptoms, furthermore, NIH has estimated that at least 10 million US men and women suffer from urinary incontinence. However, it is thought that these statistics grossly underestimate the actual prevalence of these types of illnesses. This can be partially attributed to inhibition of a patients' voiding process if someone is watching them, which often leads to inaccurate results as well as sometimes avoidance of medical help altogether. There are a number of different urodynamic tests used to assess how well the bladder and urethra store and release the urine. These tests include measuring the urine flow rate, volume, pressure, leakage, frequency, urge to urinate, urine stream, pain level while urinating, and urinary tract infections. This paper discusses multiple Urodynamic methods including non-invasive, invasive, homebased, and identifies the gaps available in current technology. In addition, the paper presents the Guidelines for Urodynamics practices developed by the International Incontinence Society. Some urodynamic tests are simple where physicians listen to a patient while urinating to understand the pattern of urination. Other techniques involve inserting a catheter into the urinary tract to measure the internal pressure of the urethra and the volume of the urine. Current methods do not enable physicians to observe the urine stream because patients need to urinate in a private setup. This results in the loss of valuable diagnostic information present in observing the shape of the stream. A new system recently designed overcomes this shortcoming, however, it requires design modifications before it can be used for women. Non-invasive methods utilizing sensors used in clinical setup provide a good insight on the urinary track. However, invasive techniques are needed to identify causes of complicated problems in urinary track.

Keywords Uroflowmetry · Urodynamics · Urine flow · Urine · Voiding volume · Bladder filling

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1 Introduction

Micturition involves two processes: (1) Bladder filling and urine storage, (2) Bladder emptying. Bladder filling requires:

1. Ability to store an increasing volume of urine at a low intracervical pressure and sensation;
2. A bladder outlet that is able to remain closed while the intracervical pressure increases;
3. Absence of involuntary contractions of the bladder.

Bladder emptying requires:

1. Smooth contraction for the muscles of the bladder;
2. Low resistance at the outlet of the bladder (sphincter);
3. Absence of obstruction [1–3].

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Urodynamic tests are used to evaluate the ability of the ureter, urinary tract, bladder and sphincter to store and release the urine. These tests range from simple observation of the voiding process to inserting catheters with pressure sensors to measure the intra-ureter pressure. One example of pressure sensor is passive senor which the design of the sensor well-described in Wang's work [4]. There are several types of Urodynamic tests [1, 3]:

- *Uroflowmetry* Aims to measure voiding volume, time, average and maximum urine flow rates. These tests involve having the patient urinating privately into a funnel that collects the urine and directs it to a measuring system to calculate the required parameters.
- *Residual Volume Measurement* Aims to measure the volume of the urine left in the bladder after the voiding process is completed. Clinicians use ultrasound to measure this volume.
- *Cystometric Test* Aims to measure how much urine the bladder holds and the pressure build up inside the bladder. These tests involve inserting a catheter with pressure sensors into the bladder and measuring the parameters while emptying the bladder.
- Electromyography tests involve measuring the electrical activities from the muscles and nerves around the bladder and sphincter.
- Video urodynamic tests involve taking ultrasonic or X-ray images of the bladder while filling up or emptying. If X-ray fluoroscopy is used, a contrast media is injected into the bladder through a catheter.

Drinnan and Griffiths presented a comprehensive description of the parameters measured in the different types of urodynamic tests described above [1].

This paper aims to discuss different techniques used in performing urodynamic tests to identify possible gaps in the available technology. The first section of the paper describes what Uroflowmetery actually measures. The second section discusses the impact of gender, position and psychology. The 3rd, 4th, and 5th sections will review non-invasive, home based and invasive methods used in uroflowmetry. Discussion and conclusions will be presented at the end of the paper.

1.1 Uroflowmetry

In Uroflowmetry, a patient is asked to privately urinate into a funnel that collects the urine into a container that has a device to measure different parameters related to the voiding process. These parameters help in evaluating the urination function of the bladder. Clinicians used to observe patients while voiding which caused embarrassment for the patients [1], therefore, current uroflowmetry techniques are designed for the private use of patients. The following parameters are the ones used to describe the urine flow (see Fig. 1).

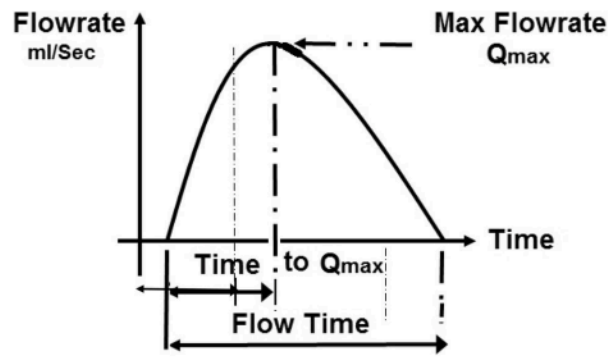

Fig. 1 Sketch of parameters describing urinary flow

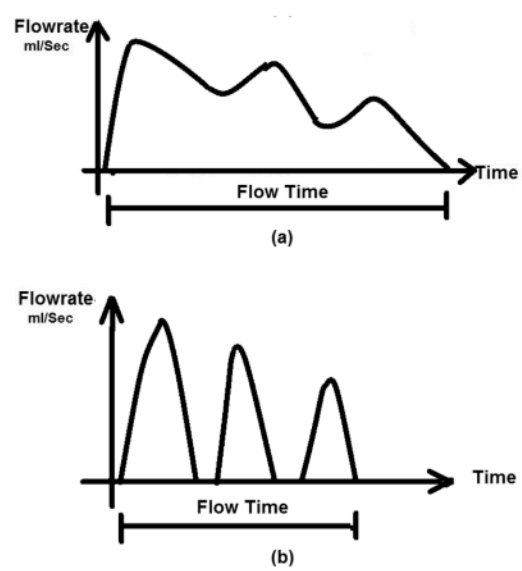

Fig. 2 Abnormal flow curve sketches, (**a**) continuous flow and (**b**) breaks in the flow

- *Flow rate Q* volume of urine per unit time and usually referred to in milliliters per second (ml/s)
- Maximum flow rate Q_{max} (ml/s)
- Voiding volume (VV) (ml)
- Flow time (TF) (s)
- Time to reach Q_{max} (s)
- Q_{ave} Average Flowrate = VV/TF (ml/s)

A normal flow pattern has a bell shape with Q_{max} reached in the first 5 s of the voiding time and the rest of the shape varies depending on the VV and time. Figure 2 shows sketches of abnormal flow curves. Some patients have breaks in the flow, in that case, the total TF is the sum of the voiding times and the break times in between.

Different flow patterns indicate different voiding abnormalities. Five flow curve patterns have been defined Normal, Prostatic, Fluctuating, Fractionated, and Plateau flow curves and each type indicates a different diagnosis [5, 6]. Q_{max} greater than 15 ml/s is normal for men where Q_{max} less than 10 ml/s is considered abnormal. For women, the normal range for Q_{max} may be between 20 and 36 ml/s [5, 7–9].

The shape of uroflowmetry curve may indicate abnormality in the urinary tract, however, further diagnosis is required to identify the cause of abnormality. Several factors affect the urine flow, the contractability of the Detrusor muscle, Bladder flow resistance, Bladder volume, and the measurement technique itself [8]. The next section of this paper will review whether or not the gender and other factors impact Urdynamic tests.

1.2 Impact of Age, Gender and Mental Status on Urodynamic Tests

Urbonavičius and Kaškonas reviewed lower urinary tract symptoms (LUTS), which affect the quality of life of older age people. They stated that one of the widely used LUTS diagnostic methods is uroflowmetry. Many variations of equipment allow performing the uroflowmetric measurements. They indicated that psychological stress and awkwardness, experienced by patients affect the results of the test. Lack of privacy while urinating is one of the factors that may cause stress to the patient. Their review showed that some methods are aimed at clinical use only [10], but there is a prominent trend of developing and producing devices that can be used by a patient in the comfort of his/her home. Different uroflowmetry techniques were discussed, including gravimetric, volumetric, image processing, acoustic, etc. and possibilities to apply these methods for men and women, as well as children [8].

Chou et al. studied the effect of urinating in women while standing instead of sitting [9]. Their study included 21 women and concluded that there is no change between Q_{max} and Q_{ave} if women urinate while standing. Amjadi et al. showed that statistically, there is no significant difference in flow rate parameters if men change their positions while urinating from standing, sitting or squatting [11]. However, this was not the case with men urinating while laying down [12].

Gomes et al. noted that in the elderly, an adequate uroflow measurement may be difficult to obtain for the following reasons [13]:

1. Geriatric patients commonly void small volumes;
2. The bladder may be empty at the moment of the study, and the patient may have urgency or urge-incontinence;
3. Mental status may be limiting and
4. Some patients have difficulty voiding in an unfriendly/unfamiliar place.

Despite its limitations in diagnosing, uroflowmetry is a sensitive indicator of voiding dysfunction and can be used to distinguish patients who will promptly need further investigation from those who can be started on a treatment regimen and avoid extensive urodynamic testing. It can also be used in patients with a known bladder outlet restriction as a measure of progression of the disease or to determine the efficacy of treatment modalities that are expected to improve bladder emptying.

Sand notes that measurement of the Q_{max} is more useful in men than in women because of its ability to detect physical obstruction of the urethra, a condition that is rare in women [14]. Uroflowmetry is primarily a measure of voiding flow rate (Q) and is measured in ml/s. Because there is little concern of physical urethral obstruction in women, the pattern of the uroflow curve is more important than the quantitative measurement of Q. A normal bell-shaped uninterrupted uroflowmetry curve is readily identified as a normal study. An abnormal uroflowmetry study shows an interrupted intermittent flow pattern, which may suggest voiding dysfunction.

Unsal and Cimentepe investigated the effect of voiding position using uroflowmetry and post-void residual (PVR) urine volume assessment in healthy men and women [15]. The study population comprised 72 healthy volunteers. The mean ages of the male ($n = 36$) and female ($n = 36$) subjects were 30 (18–40) years and 32 (21–44) years, respectively. The uroflowmetric studies were repeated in the standing, sitting and crouching positions for men and in the sitting and crouching positions for women. At least three measurements were obtained for all voiding positions for each volunteer. PVR volumes were measured using trans-abdominal ultrasound after each voiding. The parameters, Q_{max}, Q_{ave}, VV and PVR values obtained in each voiding position were compared with those obtained in the other positions.

There were no significant differences in any of the parameters between voiding positions in either group. Urinary flow rates and PVR urine volume do not seem to be affected by voiding position in healthy men and women. In conclusion, in men, uroflowmetry parameters are not affected by sitting or standing positions, however, mental situation may impact the results. The next section will review how the non-invasive techniques in uroflowmetery evolved with time and technology advancement.

1.3 Non-invasive Measurement Techniques

The first attempt made to measure urine flow rate was in 1897 by Rehfish. He used the air displaced by the urine filling an apparatus to move a pen writing on a moving paper. This system could not capture Q nor VV, however, it indicated flow patterns for the patient. The movement of the paper was not timed, therefore, Q could not be captured [16]. The method was improved by including a transducer in the system. The air displaced by the urine went over a heated wire and the energy required for maintaining the wire's temperature at 300 °C was proportional to Q. Key limitations for these techniques were the need for maintaining an airtight system and constant temperature. However, the measurements of these systems were adequately accurate and satisfactory [17].

Schwarz and Brenner indicated that the velocity of the urine stream can be approximated from the parabolic stream resulting from males voiding horizontally. This work showed that despite the discomfort for patients, directly observing their urination provides useful information [18]. They used several containers arranged in a line in front of the patient to collect the urine. The volume of the urine collected in these successive vessels and the overall voiding time calculated by a stop watch enabled them to approximate Q and VV.

Grownwell proposed the first uroflowmeter that used a pen floating on a graph paper on a moving drum. The pen was attached to a receptacle that rose as urine fell on it and the pen drew the flow against time on the paper [17].

Cardus et al. designed an electromagnetic based flowmeter to measure the urine flow [19]. They used a sensor with rubber made adaptors connected to a funnel in which both male and female patients could urinate. They calibrated the flow meter using a normal saline fluid and managed to obtain the bell shaped curve for the voiding process. Total VV was obtained by integrating the curve. This work proved that instantaneous Qcould be measured using such sensors.

Flow clinics were used since the early 1950s [20]. Patients drank plenty of water and then entered into the flow room for privacy. The clinic consisted of a flow meter installed near a bed, and an ultrasound machine to assess the residual urine in the bladder after the completion of the urination. Patients had to urinate three times and data from the flow meter together with the ultrasound analysis were combined to generate flow rate nomograms. The following shows the types of transducers used in these techniques [21–27]:

1. A weight transducer weighed the voided urine. The flowrate was determined by differentiating the volume with respect to time and the volume was calculated by using the weight and density.
2. A spinning disc. The urine fell onto a spinning disc driven by a servo motor. The torque required to maintain a constant spinning speed increased due to the weight of the urine. The power needed to rotate the disc at a constant speed is proportional to Q, and it was used to generate a flow diagram.
3. A capacitance-based flowmeter used a metal strip capacitor attached to a plastic dipstick vertically dipped into the urine container. The urine conducted electricity across the capacitance and changed the overall capacitance as it filled the container. The change in the capacitance was proportional to the flow rate.

Development in microprocessors and controllers lead to designing home-based and battery operated flowmeters that use microcontrollers. A microprocessor processes the output from the sensors and displays results. Patients can use these devices at home to record the voiding process and bring the device to the hospital to download the voiding data on a computer [28]. Artificial Neural Networks are one example of processing techniques as they were used in a system to classify the shape of the flowmetry curve as "healthy", "possible pathologic" and "pathologic" [29].

Viarani et al. simulated a resistive based microsystem flow sensor that utilized the hot wire anemometer principle [28]. These types of sensors also have been utilized in other medical applications such as sleep [30]. A heated thin film of gold with four temperature sensors covered the sensor. Q was calculated by measuring the temperature differences between the four temperatures sensors placed on the membrane while the fluid under test flowed above it. Data was fed into a computer that calculated Q and displayed the results on a digital screen.

Dejhan and Yimman designed a rotating disk based flow meter that calculated Q and displayed the results on smart phones used by the patient or the physician [21]. Otero et al. reported satisfactory accuracy for the device [22].

Carter and Vaughn introduced a toilet mounted urine flow meter [23]. The urine was collected through a funnel attached to a tubing system with mounted pressure sensor. As the urine passed through the funnel, the pressure on the sensor changed and the generated electrical signal was fed into a computer to generate a flowrate diagram. The patent did not provide information on the accuracy of the device, but such a system would involve time delay between the actual and measured urine flow. In addition, it required calibrating the pressure sensor for different flow rates. Furthermore, one of the advantages of this system was that the sensor was not in contact with the urine.

Suryawanshi and Joshi used a closed air tube located above the urine flowing into a funnel. Air pressure changes due to urine flowing above the tube were measured using a pressure sensor connected to a computer to calculate the urine flowrate. The system calculated Q_{max}, Q_{ave}, VV and other important parameters needed in uroflowmetry [24].

Wurster developed a urine flowmeter that used an apparatus that measured the volume of the collected urine versus time [25]. Flowrate was obtained by differentiating the volume with respect to time. A capacitor was used to measure the volume of the urine by designing it in a way that made the capacitance value change as the amount of urine collected changed. The electrical signal resulting from the changing capacitance was fed into a computer that was used to calculate the flowrate.

To enable male patients to undergo uroflowmetry in a private condition without medical supervision, Terai et al. devised an automatic switching and patient guidance system for the spinning disk uroflowmeter the system used two commercial electronic devices. To avoid mechanical wear of the spinning disk, an infrared motion sensor tap turns on its two AC taps when a pyroelectric infrared sensor detects human motion within 5 m. A vacuum fluorescent display (VFD) displayed a series of messages directing the patient on when to begin and stop voiding. The voided urine is drained into a wall urinal. The devices automatically turn off 5 min after the patient leaves the room. With the use of this system, men already acquainted with uroflowmetry could perform self-administered uroflowmetry any time in private. The system was considered useful for improving the quality of patient service [26].

Some researchers attempted to use the sound to measure the flowrate. A microphone was placed at the edge of the toilet seat to record the sound of the voiding process and a vessel was used to collect the urine to measure the overall volume. When the voiding process was completed, the recorded sound was played and a stopwatch was used to measure the voiding time based on the sound. This enabled the calculation of the Q_{ave} and VV. Hitt et al. attempted to correlate the sound of the urine hitting a liquid free surface with Q [31]. They designed a system that used a syringe pump with fixed flow rate to simulate the urine. The system included a digital microphone with a sampling rate of 44 kbps that recorded the splashing sound of the urine hitting a clear surface. The sound recordings were spectrally analyzed in MATLAB to evaluate the time–frequency and wavelet transform contents. This work was just experimental and did not materialize to be tested on patients. In addition, they stated that they can only make general statements about the correlation between the acoustical signature and flow parameters.

Sono-uroflowmetry (SUF) captures the sound generated by a stream of urine striking the water in a toilet bowl. Krhut et al. validated SUF using simultaneous uroflowmetry. A dedicated cell phone recorded the sound visualization showed sound intensity over time. Simultaneous sets of UF and SUF were analyzed. Correlations were for FT (0.87), VV (0.68), and Q_{max} (0.38) [32].

Wiens et al. tested an optical uroflowmeter that consisted of a camera, a filling container and lighting source contained within an enclosure [33]. A funnel directed the urine stream into the filing container, which had a vertical channel, perforated at the bottom to minimize horizontal surface disturbances. A camera imaged the volume of urine within the container as it filled. Volume data were differentiated to yield Q. The lighting source was a 5 × 6 array of white LEDs. The first frame of the video file was assigned as a background frame. Subsequent frames were subtracted from the background frame and thresholder to yield a black and white image which showed the urine surface height. When urine was clear, detection was difficult. Thus they viewed a refracted image of lines drawn on the side of the container and this image changed when urine surface height increased. They found comparable accuracy between traces resulting from the optical uroflowmeter and a Labore Urocap III uroflowmeter when a pump supplied simulated normal, abdominally strained, and obstructed flows.

Shokoueinejad et al. introduced a novel device Video Voiding Device (VVD) for Diagnosing Lower Urinary Tract Dysfunction in Men that used video cameras for recording the voiding process and then calculates some of the important parameters for diagnosing lower urinary tract dysfunction [34, 35]. The system has three positioned cameras. A side camera views the urine stream from a 90° horizontal angle on a black background. A top camera views the urine stream from a 90° vertical angle on a black background. A lower back camera (the cylinder camera) monitors the accumulation of urine into a 1000 ml cylinder. LED Spot Lights illuminated the stream to provide best contrast. Two LEDs were mounted on the wall facing the patient (above and below the urine stream line of action). One LED was mounted at the top of the right side wall, shedding light from a steep downward orientation/trajectory towards the funnel. The combination of these three LED placements shedding light from three different angles results in complete illumination of the urine stream, ensuring high contrast and visibility.

To use the VVD, the patient stands in front of the device and urinates. The urine is guided by a large 53 cm diameter funnel leading it to the cylinder. The urination is captured from two angles using two cameras (top and side). The cylinder camera captures the filling process of the cylinder in order to compute the instantaneous flow rate, Q_{max}, FT, and VV. MATLAB was used to analyze the video recording of the urine accumulating in the cylinder and to calculate the instantaneous Q, Q_{max}, FT, and VV.

The device was clinically tested on patients. It allowed patients to urinate privately and gave urologists the advantage of observing the video of the voiding stream giving them the ability to determine any abnormalities or obstructions in the urinary tract. The accuracy of the measurement was tested by integrating a mass flowmeter into the setup and simultaneously measuring the instantaneous flow rate of a predetermined voided volume in order to verify the accuracy of the device compared to the mass flowmeter. The accuracy recorded was ± 2 and ± 3% relative to full scale.

In summary, interest in calculating the urine flowrate began in the 20 s of the previous century. The technology evolved with time, initially, flow sensors were used, later, these sensors were integrated with microprocessors and smart phones to make more analysis and broadcast the information between the patient and physicians. Disposable home used devices were introduced; however, they can perform limited measurements to indicate whether a problem is there or not.

Uroflowmetry methods discussed so far were non-invasive and used in the clinic, the next section will review some of the invasive techniques used in the field.

1.4 Home Based Uroflowmetry Technique

Home based urine flow measurement techniques can be as simple as dividing the volume of the voided urine measured in a collection vessel by the voiding time calculated by a stopwatch and obtaining Q_{ave} rather than Q_{max}. Hand-held funnel based devices can also be used at home. Users void into a funnel. The urine flows out of the funnel into a restricted aperture into a measuring container; the aperture contains a flow sensor calibrated for several ranges of flow rates [36]. The accuracy of these devices can be measured by dropping a fluid in them at a controlled and known flowrate and then comparing the recorded flowrate with the actual known one. These flowmeters have clinically accepted results if the volume error is 1–8% and Q errors 4–15% [36, 37]. Drach and Binard used a portable flowmeter made of plastic consisting of two chambers opened on each other. A strip that changed colors in steps of 2 ml/s was used to calculate the Q_{max}. The reported accuracy of the system was ± 1.5 ml/s of Q_{max}. The device was disposable, easy to use and could be used to calculate the Q_{ave} if the voiding time was calculated [38].

Caffarel et al. showed that calculating the average value for Q_{max} measured multiple times at home improves that accuracy of the measurement and brings it closer to the value measured using uroflowmeters within clinics [37, 39]. They asked 22 patients to record their Q_{max} twice a day for 12 consecutive days. In addition, they used a rotating disk based urine flow meter in the clinic to measure Q at the start and end of the 12 days. The mean values for home base uroflowmeters and rotating disk flowmeter showed good agreement.

The Streamtest cup is a simple device to evaluate urine flow at home or in a Urology clinic [40]. It is basically a plastic disposable cup with an exit tube in the bottom center of the cup. The exit tube was designed to allow a Q_{max} of 12 ml/s. A marker was placed near the bottom of the cup representing a 200 ml of urine filling the cup while exiting from the bottom of the cup at the same time with a rate of 12 ml/s. If a patient urinating in the cup at a Q less than 12 ml/s, then the urine never reaches the marker in the cup indicating a problem in the urinary tract. If the urine reaches the marker and begins to over flow the cup, then Q is higher than 12 ml/s and the urinary tract is normal. The system was tested on 50 patients and all patients with Q higher than 12 ml/s overflowed the cup and those with Q less than 12 ml/s didn't manage to reach the marker. The system provides an insight on the Q but cannot measure the instantaneous flow rate. Severely obese and visually impaired patients may not be able to observe the marker on the cup while urinating.

De La Rosette et al. designed a home based portable uroflowmeter and compared its performance with another system based in a urology clinic [41]. The portable flowmeter consisted of four calibrated volume sensors printed on paper-like disposable material. The paper was shaped like a cone placed in a beaker to collect the urine. The electrical properties for the volume sensors varied as the fluid volume increased in the beaker. The system was connected to a microcontroller that calculated the flowrate and stored it in its memory. The performance of this portable system was compared with an invasive catheter based uroflowmeter system with 67 patients. Comparison results showed that home based uroflowmeters can provide reliable measurements for the voiding process.

Another disposable home based uroflowmeter to calculate Q_{max} and VV comprised a collecting funnel with a sprout divided into three chambers. The device was pre-calibrated such that filling of the chambers corresponded to Q_{max} values of 10, 10–15 and 15 ml/s. The performance of this device was compared with a standard flowmeter. The study involved 46 men who were asked to use the funnel at home twice a day for 7 days. Results showed that the device has sufficient accuracy and reliability to give an initial assessment for Lower Urinary Tract Diseases [42].

Jørgensen et al. tested the Da Capo™ home flowmeter versus the Urodyn 1000™ flowmeter. The two flowmeters are based on different principles [43]. The Da Capo is a portable, battery powered flowmeter designed to record all voidings during a period of time (e.g. 24 h) for a single patient. The flowmeters were tested with regard to accuracy of measurement of VV and Q_{max}. The Da Capo was tested by 10 healthy male volunteers, median age 47 years, range 21–57. Both flowmeters were very accurate measuring Q_{max} and voided volume. A few artifacts arose, i.e. extremely high Q_{max} values were recorded. All test persons found the flowmeter easy to handle. The weight transducer based Da Capo home flowmeter proved as accurate as the stationary flowmeters. It is easy to handle and it provides all-day monitoring of flow and voided volume.

Guan et al. designed a new portable home electronic uroflowmeter and compared it with traditional methods. The system consisted of collectors, urine conducting apparatus, intelligent cell phone, wireless technology, computer analysis, and data storage. The system automatically collected voiding information from patients with lower urinary tract symptoms (LUTS) [44]. The information was sent via Bluetooth to the patient's cell phone where it was stored and transmitted to the workstation in hospital.

The system was primarily tested with regard to accuracy of measurement of the voided volume. Multiple doses with known volume were introduced in the system and in calibrated uroflowmeter in lab settings. 38 outpatients who had LUTS were tested simultaneously with the system and the Lab uroflowmeter. Among the subjects, there were 22 male patients and 16 female patients, with a total of 57 tests. The system accurately collected and analyzed voiding time, VV, and automatically provided uroflowmetry parameters. The measurement error at 100, 200, 300, 500 and 800 ml was less than 5%. As for Q_{max}, Q_{ave} and VV, 12.28, 5.26 and 3.51% of the points were beyond the 95% limits of agreement. The maximum absolute values of the Q_{max}, Q_{ave} and voided volume differences were 0.38, 0.70 ml/s and 2.90 ml, respectively. They agreed with the recommendation of Standardization International Continence Society. The new portable home electronic uroflowmeter had good agreement with the Lab uroflowmeter, and is a new LUTS monitoring system integrated with correct, reliable, real-time, convenient and easy-managing advantages. It is as noninvasive and reliable as traditional methods, and its portable feature facilitates application out of hospitals. It can also record voiding diaries.

Chan et al. found electronic uroflowmetry reasonably predicts the likelihood of bladder outlet obstruction (BOO) and risk of acute urinary retention (AUR) [45]. To show the clinical value of a simple flowmeter, which has been devised to measure uroflow on an ordinal scale (< 10, 10–15, 15–19 and > 19 ml/s) at home, for the management of male LUTS a total of 186 men with LUTS were enrolled in the study. The mean follow-up was 220 days. The mean age for men was 65.5 years, mean (range) Q_{max} 12.8 (4.3–39.5) ml/s, mean (range) VV 294.8 (151–686) ml; mean (range) post-void residual urine volume (PVR) 50 (0–303) ml and mean (range) International Prostate Symptom Score (IPSS) 13.5 (1–31). The men underwent electronic uroflowmetry ('clinic uroflowmetry') and completed an International Prostate Symptom Score (IPSS) questionnaire in the clinic. They then conducted 10 measurements with the device at home ('home uroflowetry'). The uroflowmetry and IPSS questionnaire were repeated 2 weeks later. The sensitivity and specificity of the home uroflowmetry values corresponded to the mean Q_{max} of clinic uroflowmetry. Similar analyses were performed for the IPSS.

Home uroflowmetry worked better in identifying a mean Q_{max} of > 19 ml/s, and a mean Q_{max} of < 10 ml/s. The home uroflowmetry works best in ruling out a mean Q_{max} of < 19 ml/s followed by a mean Q_{max} of < 15 ml/s and a mean Q_{max} of < 10 ml/s. Men with a home uroflowmetry value ≤ 10 ml/s were more likely than those with a home uroflowmetry value > 10 ml/s to develop AUR or require TURP. The IPSS failed to display the same discriminative capability. Home uroflowmetry using this simple device is a satisfactory estimation of clinic uroflowmetry using an electronic flowmeter and can predict the significant progression of male LUTS.

Boci et al. studied home uroflowmetry and compared this method to free or "traditional" uroflowmetry in the evaluation of patients with symptomatic benign prostatic hyperplasia (BPH), and the relationship between the values of home uroflowmetry parameters and bladder outlet obstruction (BOO) [46]. Twenty-five patients (mean age, 67 years) with symptomatic BPH were examined with home uroflowmetry, free uroflowmetry, and pressure-flow measurement. The patients were assessed using the International Prostate Symptom score (IPSS); digital rectal examination; routine blood chemistry, including serum prostate-specific antigen level; urinanalysis; transrectal ultrasonography; and post-void residual urine. The 24 h were divided into "active time" (AT) and "sleep time" (ST). AT home uroflowmetry parameters were compared to ST ones. A total of 485 flow measurements were recorded during 2 day period for the study. After visual evaluation, 429 flows (88.45%) were included in the study.

The home uroflowmetry parameters were compared to respective ones of the free uroflowmetry as well and those obtained by pressure-flow measurement. The patients were asked about their opinion of home uroflowmetry. Home uroflowmetry was found to be a simpler and more acceptable method than free uroflowmetry. The mean of Q_{max} of AT was significantly greater than the mean *of* Q_{max} of ST, but the mean voided volume and mean voiding time of ST were significantly larger than those of AT. There was a close relationship between the mean of Q_{max} at home and the Q_{max} in hospital, but the voided volume and voiding time measured in hospital were significantly larger than those at home. Home uroflowmetry provided an estimation of BOO for 46% of the patients as low if the home mean of Q_{max} was > 14 ml/s, and as high if the home mean *of* Q_{max} was < 10 ml/s. Home uroflowmetry was well accepted by the patients and gave more information than free uroflowmetry. In 46% of the cases, an estimation of BOO was obtained with home uroflowmetry.

Mombelli et al. investigated the possibility that patients could carry out a urine flow assessment at home by themselves, in comfort, without expense and without the use of equipment [47]. They compared this strategy of "Do-It-Yourself" (DIY) uroflowmetry with traditional, hospital uroflowmetry. One hundred and twenty patients were enrolled. The patients underwent conventional, free uroflowmetry in hospital. Subsequently, the patients were asked to carry out the following procedure at home: urinate into a graduated container to quantify the total voided volume and determine the flow time by measuring the duration of micturition with a stopwatch or simply with the second hand of a clock. This procedure had to be performed three times without preparation. One hundred patients completed the study. The mean age of the patients analyzed was 64.12 years. The proposed DIY evaluation of urine flow, together with the International Prostatic Symptom Score (IPSS), provides a good estimate of the results of free uroflowmetry, enabling unnecessary hospital investigations to be avoided.

Home based devices can be used to have an initial diagnosis of the lower urinary tract, however, they don't measure all the uroflowmetry parameters, therefore, they can be used as an initial method to determine whether further analysis is needed or not. The next section of this paper will discuss the invasive techniques used in uroflowmetry without getting into much detail since the objective of the papers is to identify the added value of the newly developed VVD system which is not invasive.

1.5 Invasive Measurement Techniques

The flow rate is a function of the internal pressure in the bladder and hydraulic resistance of the urinary tract. Since non-invasive uroflowmetry focuses on external measurement, it can only be considered as a good diagnostic tool to determine abnormal flow patterns. It gives very little information on the causes of abnormalities.

Cystometry is a technique that measures the storage abilities of the bladder and determines the relation between the pressure in the bladder, resistance of the urinary tract, and the voiding process. It uses internal pressure sensors to measure both the abdominal P_{abd} and bladder pressures P_{blad}. The difference between these two pressures together with the flow rate can be used to calculate the resistance of the urinary tract as well as many other parameters that can be used in diagnosing problems in the urinary system [8, 48].

Fluoroscopy techniques utilizing X-ray technology are also used to diagnose the micturition process (filling and emptying the bladder) [20, 49, 50]. Images of the urinary tract can be made while coughing, sneezing, at rest, while voiding and filling are taken and used to diagnose the patient problem [48] but since X ray and invasive pressure and flow sensors are involved, this procedure is used with patients with severe complications [51], this invasive pressure measurement also be used in measurement of intracranial pressure [52]. Nuclear Medicine based methods are also used. Patients are orally given a liquid isotope and after 40–60 min, a scintillation detector measures the amount of the collected urine in the bladder. But since the method involves using isotopes, it is not a commonly used technique. Furthermore, this technique does not give Q nor the VV and requires a long time.

Electromyography is also used to measure the contraction of several muscles in the urinary system using invasive electrodes placed on the bladder and sphincter of the subject [48].

In an attempt to explore whether noninvasive methods are enough to diagnose lower urinary track symptoms (LUTS), Reynard et al. explored the relationship between uroflow variables and LUTS. The objective was to define performance statistics (sensitivity, specificity, positive and negative predictive values) for Q_{max} with respect to bladder outlet obstruction (BOO) at various threshold values; and to investigate the diagnostic value of low-volume voids [53].

The study comprised 1271 men aged between 45 and 88 years recruited from 12 centers in Europe, Australia, Canada, Taiwan and Japan over a 2-year period. Symptom questionnaires, voiding diaries, uroflowmetry and pressure-flow data were recorded. The relationship between uroflow variables and symptoms, Q_{max} and BOO, and the diagnostic performance of low volume voids were analyzed. The relationship between symptoms and uroflow variables was poor. The mean difference between home-recorded and clinic-recorded voided volumes was –48 ml. Q_{max} was significantly lower in those with BOO (9.7 ml/s for void 1) than in those with no obstruction (12.6 ml/s; $P < 0.001$) and Q_{max} was negatively correlated with obstruction grade, even when controlling for the negative correlation between age and Q_{max}. A threshold value of Q_{max} of 10 ml/s had a specificity of 70%, a positive predictive value (PPV) of 70% and a sensitivity of 47% for BOO. The specificity using a threshold Q_{max} of 15 ml/s was 38%, the PPV 67% and the sensitivity 82%. Those voiding < 150 ml had a 72% chance of BOO (overall prevalence of BOO 60%). In those voiding > 150 ml the likelihood of BOO was 56%. The addition of a specific threshold of 10 ml/s to these higher volume voiders improved the PPV for BOO to 69%.

While non-invasive uroflowmetry cannot replace pressure-flow studies in the diagnosis of BOO, it can provide a valuable improvement over symptoms alone in the diagnosis of the cause of lower urinary tract dysfunction in men presenting with LUTS. This study provided performance statistics for Q_{max} with respect to BOO: such statistics may be used to define more accurately the presence or absence of BOO in men presenting with LUTS, so avoiding the need for invasive pressure-flow tests in everyday clinical practice. This study also shows that low-volume uroflowmetry can provide useful diagnostic information and that, as such, the data from such voids should not be discarded.

The previous sections discussed many Uroflowmetry methods. The next section of this paper discusses standards developed by professional societies to govern Uroflowmetry devices

1.6 Guidelines for Good urodynamic Practice

The international continent society (ICS) developed comprehensive guidelines for Good urodynamic practice in both clinical and research investigation [5]. The guidelines covered three main elements (the measurement practice, the quality control, and documentation). It went over the various techniques used and suggested guidelines for using it.

The guidelines stated that urodynamic practices cannot be fully automated except for uroflowmetry. The accuracy for flowrate measurement needs to be ± 1 ml/s, with a flowrate range between 0 and 50 ml/s and a total VV of 1000 ml with many other documentation and safety requirements. One of the techniques used in uroflowmetry is the flow curve shown in Fig. 1. Some flow curves may show abnormality, however, the guidelines state that a diagnosis cannot be made using flow curves alone. Further invasive measurements for the pressure in the bladder are needed to have an accurate diagnosis for any abnormality appearing on the flow curve.

Note that the flowrate measurement and the flow curve are affected by the signal processing involved and the method used to calculate them. A collecting funnel, or tubing used to direct the urine, or the flow sensor will eventually cause modification to the actual flowrate. Therefore, the guidelines stated that an electronic measurement of Q_{max} requires smoothing the flow curve by averaging over 2 s to remove the spikes in the signal. In addition, a minimum rate of 10 Hz is required for the analog to digital conversion. ICS also required that the Q_{max} should be rounded to the nearest whole number while the voiding and residual volumes should be rounded to the nearest 10 ml [5].

The guidelines developed by ICS in 2002 went further to provide information on quality measures required for invasive pressure-flow measurements. It stated that typical information such as VV and Q_{max} should be obtained from non-invasive techniques before moving towards invasive ones.

In 2014, the ICS published more updated guidelines to serve as a benchmark for the performance of urodynamic devices [51]. The guidelines aimed to provide a summary for the performance requirements, technical specifications, and comparison of different technologies used in urodynamics. Furthermore, the guidelines proposed a set of tests for assessing of different systems.

The updated guideline suggested that any urodynamic system should be able to measure the difference between the intra-vesical and abdominal pressures together with Q and VV. Clinicians may require additional measurements such as urethral pressure and the electromyography signal (EMG) of urethral muscle by using well-designed bio potential measurement electrodes [51, 54]. The updated guidelines did not change the clinical values introduced in the previous version as shown below:

- Accuracy of Q measurement should be ± 1 ml/s.
- The resolution of the VV should be at most 2 ml with a ± 3% error in the value.
- The range of Q measurement necessary is 0–50 ml/s, with a VV range of 0–1000 ml.
- Sample rate of VV measurement ≥ 2 Hz.
- Bandwidth between 0 and 5 Hz is recommended to record Q with a sampling rate of at least 0.2 Hz.
- A low pass filter with a cutoff frequency of 1 Hz needs to be used to smooth and average the flow curve.

The guidelines added desirable features for uroflowmetry equipment that included the need to state the minimum recordable volume or flowrate change. In addition, documentation should indicate the signal processing method used in the measurement.

Flowmeters need to be able to measure low flowrates that have clinical significance. Obstructed bladder may lead to very low flowrate and it is important to be able to capture that measurement. A device should be able to measure down to its accuracy of 1 ml/s and this number should be mentioned in the documentation associated with the device.

Requirements on some of the common technologies used in uroflowmetry were included in the guidelines.

The load cell flowmeter (gravimetric) flow meters rely on fluid weight measurement during voiding. Volume of urine can be calculated by dividing weight by density. Flow is change in the volume with time. The guidelines required the scale to remain horizontal for reliable measurement. A set zero volume function should be available to overcome the difficulty of emptying the flowmeter between voids.

The spinning disk flowmeter or momentum-flux flowmeter is also used in uroflowmetry. Urine falling on a spinning disk slows it down; therefore, more power is needed to keep the disk rotating at the same speed. The flowrate is proportional to the power needed to keep the disk rotating at a constant speed. This method enables calculating the mass flow directly without the need for using the density of the urine as is the case with the load cell method. The volume can be calculated by integrating the flow.

Dipstick methods for measuring flow use a capacitive stick dipped into a container that is filled with urine. The change in the capacitance is proportional to the flowrate. The guidelines stated that the method was proven reliable but no clinical publications were associated with it. Drop spectrometry is another method mentioned in ICS guidelines; however, it was technically demanding and unreliable.

The ICS guidelines required a calibration method for uroflowmeters. After 10 voiding measurements, a volume of 300 ml of water is poured into the device as a constant Qto verify its operation. Another method is to empty the urine collected from a device into a measuring beaker to verify

Table 1 Summary of uroflometry methods

Method Type	Technique	Measured quantities	Where to use	Cost	Accuracy
Invasive	Catheter with flow and pressure sensors	Q, internal and external pressure, path resistance	Clinic	High	High
	Fluoroscopy (camera with contrast agent)	Ureter function (X ray)	Clinic	High	High
	Myography (electrodes)	Internal muscles and sphincter contraction activity	Clinic	Moderate	Moderate
Noninvasive and can be integrated with a micro-processor	Ultrasound	Residual urine volume in ureter	Clinic	Moderate	Moderate
	Hotwire temperature	Q	Clinic	Low	Moderate
	Floating pen on a moving drum	Flow diagram, Q_{max}, TF	Clinic	Low	Moderate
	Electromagnetic sensor	Instantaneous flow rate	Clinic	Low	High
	Weight based sensor	Q_{max}, VV, flow diagram	Clinic	Low	High
	Spinning disk	Q_{ave}, VV, flow diagram	Clinic	Low	Moderate
	Capacitive sensor	Q_{ave}	Clinic	Low	High
	Resistive thermistors	Q_{ave}	Clinic	Low	Moderate
	Pressure sensor with tubing and funnel	Q_{ave}	Clinic	Low	Moderate
	Handheld funnel calibrated to a certain flow rate	Determine if flow exceeds certain values or not	Home	Low	Low
	Microphone sensing voiding sound	Q (not proven clinically)	Home	Low	Low
	Video camera	Q, VV, instantaneous flow rate, FT, Q_{max}, Q_{min}, Q_{ave}	Clinic	Low	High

the value of the collected volume. If the flow sensor requires calibration frequently, then it might be better to replace it.

Many possible sources of errors were mentioned in the ICS guidelines; designs of device should account for them and adjust performance to compensate for them:

- Load Cell method: The density of the urine used is 1 g/ml which might not the case with patients using contrast medium or having dehydration. Allowing the user to modify the density in accordance with patient conditions may reduce its effect.
- The momentum of urine falling on the spinning desk may cause artifact in the volume calculated.
- Time delay between the change in ureter pressure and urine flowrate, in addition, low pass filtering techniques used in signal processing will cause further delays. ICS estimated the delay to be 0.4–0.6 s.

The next section of this paper will provide a summary for all the systems reviewed so far and identifies the novelty of the VVD system developed.

2 Discussion

Urodynamic studies are used to diagnose lower urinary track diseases. They involve noninvasive methods (usually referred to as uroflowmetry), homebased methods, and invasive methods (usually referred to as cystometry). The complexities of these tests vary depending on the method used and the measured parameters. Table 1 presents these techniques and some parameters associated with them.

Non-invasive systems using electronic sensors require special tubing and funneling setup, therefore, they are not portable and mostly used in clinics. There is little innovation in developing new sensors for measuring flowrates. However, development in signal processing, microprocessors and mobile applications resulted in designing systems that use existing sensors to make more measurements, provide more convenience for physicians and clinicians. Magnetic, capacitive, and weight-based sensors directly measure the flowrate. Capacitive, hotwire, thermistor, pressure, and spinning disk-based sensors indirectly calculate the flow by measuring the change caused by the flow in capacitance, temperature, torque and pressure. This indirect measurement results in an accuracy that is lower than the one associated with methods involving direct measurement. The cost for non-invasive devices is moderate since they use simple electronics that is widely available in the market. However, the risk and cost involved in invasive testing is quite high, therefore, physician are keen to use methods that can diagnose the urinary track non-invasivly. Unfortunately, non-invasive tests assist in identifying the existence of a problem and narrowing it down to multiple possibilities. However, invasive techniques are required to identify the exact problem.

A new system VVD designed and tested provides a video recording of voiding process recorded while preserving patient privacy. The video recordings together with the calculated parameters will enable the physicians to have more insight on possible abnormalities in the urinary track. A limitation of the new system is that it requires design modifications before it can be used for women.

Guidelines of International Continence Society for designing new uroflowmetry devices are well developed. Scientists and experts have published multiple versions of them. These guidelines help in evaluating new techniques proposed by inventors and researchers.

3 Conclusion

Urodynamic methods including invasive, non-invasive and homebased were discussed in the paper. Urodynamic tests have evolved with time, new systems are utilizing the advancement in microprocessors, mobile applications and signal processing tools. Despite these advancements, physicians could not obtain full diagnosis to LUTS via non-invasive methods and the need for invasive methods still exists. A newly developed system VVD for men only provides privately taped videos of the voiding process, which enables physicians to observe the urine stream. This new insight may reduce the need for invasive testing methods.

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